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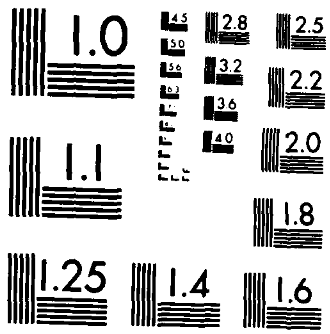

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AD-A155 920

ANALOG, STILL WITHOUT FEAR

BY DR. ARTHUR D. DELAGRANGE

UNDERWATER SYSTEMS DEPARTMENT

1 SEPTEMBER 1984

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NAVAL SURFACE WEAPONS CENTER

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85 6 3 122

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: NSWC TR 84-360 / 2. GOVT ACCESSION NO.: AD-A155 920	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): Analog, Still Without Fear	5. TYPE OF REPORT & PERIOD COVERED: Final
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Dr. Arthur D. Delagrange	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Naval Surface Weapons Center/White Oak (U21), 10901 New Hampshire Avenue, Silver Spring, MD 20903-5000	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: AA17C4912 0609212E 3789000 000000
11. CONTROLLING OFFICE NAME AND ADDRESS	12. REPORT DATE: 1 September 1984
	13. NUMBER OF PAGES: 35
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution is unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Analog Circuits
Linear Circuits
Integrated Circuits
Operational Amplifiers
Active Filters

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report is an update of one issued in 1977 which predicted that the predicted death of analog circuitry (also called "linear") would not occur; in fact, the patient appeared remarkably healthy. The report proved correct. We have the same situation again today: the same predictions and counter-prediction. Each year brings significant advances in the field of analog integrated circuitry. Many of the traditional arguments against analog circuitry are no longer valid.

This report attempts to summarize what is available now, and what can (and

cannot) be done with analog integrated circuits. It defines analog and makes some comparisons with digital. The most common types of analog integrated circuits are then listed and discussed. Lastly, some design and trouble-shooting hints are given, and the state-of-the-art is discussed.

FOREWORD

This report is a general paper describing analog (linear) integrated circuitry. It is an update of one written in 1977 which has become out-of-date due to the rapid growth in the industry. It will be of interest to persons working with electronic circuitry, particularly signal processing or analog circuitry.

Approved by:

A. M. JOX, Head
Surface ASW Division

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CHAPTER 1

INTRODUCTION

This report is an update of one published in 1977. In seven years, the original has become out-of-date in some respects; in others, it has not. At that time the death of analog was being widely announced. However, the corpse refused to lie down. It was this author's contention at that time that analog, far from being dead, was thriving. One problem is that in our society number two is considered a loser, even in a field of hundreds. The rate of advance of the analog art greatly exceeded almost any other discipline around, digital being an obvious exception.

The situation has not changed. It seems that fortune tellers, weather forecasters and doomsayers will always be with us, no matter how inaccurate their predictions prove to be. We are now told that analog is more dead than ever before; that digital can now do anything that analog can. Aside from the problem that the statement is simply not true, the important question is, "Should it?". It has been demonstrated that a house can be built out of empty beer cans, but more people still use brick, even those who generate a sufficient quantity of empty beer cans. The designer who is a real prize is the one who appreciates both digital and analog and the advantages and disadvantages of each.

Analog continues to grow at an exponential rate, and the end is not in sight. National Semiconductor's gross external sales of analog integrated circuits for the previous operating year was approximately half a billion dollars. Considering that many of these units sold for less than one dollar, this is equivalent to saying that roughly every man, woman and child in the U.S. bought an analog integrated circuit last year, not even counting the other companies' sales. This does not indicate a dead industry.

Probably even more important than the quantity or the dollar value of analog sales is the variety available, particularly the rate at which it is increasing. New devices have functions not available before. Better ways of doing old jobs have been developed. Individual specifications have been improved, some beyond what was thought possible seven years ago. Although analog design is more complicated now in the sense that so much more is available to choose from, it

has become easier in the respect that for any given problem the better devices available leave less work for the designer. Virtually every device sold today is something the "experts" had at one time predicted would never be possible.

A strong case can be made that the majority of electronics in the world at this time is still analog. Of course this depends entirely on how one chooses to count, but consider that of consumer electronics (television, radio, audio, telephone), nearly all is still analog. This is changing rapidly, as most new systems are digital and some old ones are being converted, but it is not all one-sided. Note that the telephone has moved away from digital in the sense that the numbers "dialed" are now transmitted by tones in place of the old on-off scheme. Then there are always the philosophical arguments: that everything is really analog because a digital circuit cannot get from a zero to a one without traversing the continuous space in between; or that everything is really digital because electrons are quantized. We will leave those discussions to people having nothing better to do.

This report is simply a survey of what is available in the analog world today. It cannot list all devices; it takes a 500-page catalog just to list the basics[1]. Likewise, consideration was given to including some specification sheets, but it would have been possible to cover only a few devices. Manufacturers' catalogs comprise a stack well over a foot high, and much of that is print too small to reproduce well. Therefore this report will be limited to general descriptions, with some type numbers so the reader may refer to a catalog.

CHAPTER 2

WHAT IS ANALOG?

The most convenient definition of analog is all electronic circuitry not clearly digital (two-level logic). Some things are specifically excluded, such as power distribution and radio frequency. Analog is sometimes called linear, referring to the fact that analog may take on a continuous range of values as opposed to discrete steps, but this is a misnomer as analog includes a great deal that is not linear. Therefore this report will use analog.

The term is a holdover from analog(ue) computers, the first electronic computers. They solved problems by setting up an electronic circuit "analogue" of another system (e.g., mechanical) governed by identical equations and then observing the behavior of the electrical system. Tests could be run quicker and parameters more easily varied. Nowadays this task is done by general-purpose digital computers, and changes done in software. However, the circuits and techniques developed for analog computers were general enough that they found other uses and survived, principally in smaller special-purpose systems.

CHAPTER 3

WHICH IS BETTER, ANALOG OR DIGITAL?

This is a classic question, for which no general answer exists as yet. At best it can be applied only to a specific problem; at worst, it is comparing apples and oranges. And what is the standard for better? From the Navy's point of view, most "cost-effective" is probably the best term. In general, one must take a given system, design it with both analog and digital, and see which design appears better. In some cases only one alternative is practical. In many others the following guidelines will help.

First, consider the input(s) and output(s). If both are digital, the system in between would logically be digital (no pun). If one or the other is digital, the usual practice is to carry the digital as far as possible, then convert to analog and do the rest. The real world, including normal human beings, is almost entirely analog. Hence real-world sensors usually have an analog output, often at low level, which may require considerable analog preconditioning before an Analog-to-Digital (A-D) converter can handle it. A digital system often outputs to humans by video or audio; usually the Digital-to-Analog (D-A) conversion is as near the end of the process as possible. If the system is to be analog on both ends, it is simplest to keep the entire system analog if possible. Some other considerations which may decide the question are:

(a) Accuracy. Analog is limited to about 0.1%, equivalent to 10 bits. The accuracy of a digital machine can be improved by increasing number of bits. If one is plotting a trip to the moon, one should use a digital computer. For a trip to the grocery store, an analog gas gauge works fine.

(b) Bandwidth. Broadcast FM (Frequency Modulation) cannot be digitized completely because this would increase the bandwidth beyond the allowable limits. FM already takes ten times the bandwidth of AM (Amplitude Modulation).

(c) Sampling. The classic case is replacing an analog low-pass filter with a digital filter. It still requires an analog low-pass filter on the front end to prevent aliasing (sampling) errors, so it is not really true to say the analog filter has been replaced.

(d) Power Dissipation. Lowest power dissipation can go either way, depending on a number of factors such as operating speed, possible multiplexing, etc.

(e) Cost. Both types of system may be feasible, but with a great disparity in cost. Accounting must include all costs, for example, making adjustments or programming time. These in turn depend heavily on other factors such as the number of units to be built, accessibility after installation, etc.

CHAPTER 4

RELIABILITY

Reliability is certainly one of the most important factors, but it is considered separately here because it is not at all clear whether analog or digital is better in this respect. There is an ongoing raging argument, and strong points can be made on both sides. Many decisions are based on information that is no longer valid.

The very first problem is that the definition of failure is not only different for the two technologies, but is surprisingly unclear. For digital, any bit being incorrect constitutes a failure, but failure of a low-order bit may not produce enough error to cause system failure. For analog, failure is usually defined as going out of specification, but a system may still be usable enough that the mission will succeed. Again, we must take it case by case. Some factors to consider are the following:

(a) Sudden System Failure. Analog systems usually degrade gradually, while digital tend to work right to the bitter end and then fail suddenly. One or the other may be less desirable, depending on the situation.

(b) Temperature. The temperature range depends basically on the semiconductor material and hence is the same for both. Note again that analog will drift, while digital quits. Note also that higher power dissipation means higher operating temperature on the chip, which is where it counts.

(c) Supply Voltage Sensitivity. This depends on the specific type. Analog typically works over a wide range, but usually drifts. CMOS digital works over a wide range, but TTL is fussy. Systems of both kinds have been observed to work in spite of complete regulator failure! This can be important, as battery/power supply failure is probably the biggest single cause of system failure.

(d) Static Electricity Susceptability. Again, this depends on the specific type used in either case. MOS is the most sensitive and has acquired a bad reputation which is undeserved, as other types can be affected, too. The best rule is that anything can be damaged, but anything will work if proper precautions are taken.

(e) Accidental Shorting. Again, it depends more on the specific type used. Both are much better than they used to be.

(f) Overvoltage. Depends on range and normal setting; see (c) above.

(g) Voltage Reversal. Generally no type will survive this. Diodes can be used for protection if reversal is likely.

The reader can no doubt recall bad experiences with both types of systems, for example television sets or computers. There seems to be a natural tendency for man to push any system to its limits, which leaves little margin before failure occurs. In this author's opinion, the overriding factors are system design, quality of parts, quality of assembly, etc., not analog vs. digital. Reliability can be predicted, but this is only an average based on experience. A small number of systems will generally be either considerably better or considerably worse than expected, usually worse. Most failures are batch-related, so a small lot tends to be either all good or all bad. If a digital system resides mostly in a single processor chip, it has a good chance of sucess once that chip has been screened. On the other side, some analog filters having a large number of parts actually tend to have better overall tolerance than the individual parts due to statistical averaging, and sometimes perform decently even with the complete failure of some (non-critical) part! In either case, reliability tends to get better as more units are produced, because of the "learning curve".

the technology has reached. Most existing devices were designed for specific applications such as TV ghost cancellation, audio effects, or correlators, but they inherently have other possible uses; some general-purpose devices are appearing. Undoubtedly, better availability will generate more uses, and vice-versa.

ACTIVE FILTERS

One of the classic quests of electrical engineering has been to design the ideal filter, usually defined as a device which passes one part of the frequency spectrum without alteration while totally rejecting the rest of the spectrum. It can be shown that such a device can only be approximated. Digital systems can come close, but are complex and require A-D and D-A converters and a linear prefilter, and cannot perform in real time at higher frequencies. General-purpose digital-filter ICs are just beginning to appear.

A single general analog filter does not exist either. There are several tradeoffs involved, and consequently a large number of circuits have been thoroughly developed [25], most aimed at optimizing a particular parameter. Fortunately, in most practical applications some parameters are not critical, and there is at least one type of filter that will perform adequately. The original filters were passive [26]; modern designs are usually active [27] (inductorless), at least at low and medium frequencies. Active filter circuits are usually built around op-amps, and are not themselves complete ICs.

One rather general type that does lend itself to integration is the Universal Active Filter (UAF), appearing in a number of variations under several names, such as "state-variable", "biquad", and "biquartic". It is basically a resonator consisting of two op-amp integrators, one inverting and one noninverting, in a loop, with negative feedback added somewhere for damping. By placing input and output at appropriate places, the circuit can be made to function as high-pass, low-pass, or band-pass. With the addition of a fourth op-amp as a summing amplifier, band-reject and all-pass functions are also available. The resonant frequency and "Q" can be set to any value desired, limited only by the performance of the op-amps. Theoretically any realizable filter function may be achieved by placing enough of these having the proper pole-pair (and zero-pair if required) frequencies in tandem, with a single pole (or zero) simple RC added if the order is odd. In practice, for any given filter type there is usually a specific circuit that is better for that type than the UAF. In fact, for some designs the UAF is not practical at all.

Obviously, UAFs may be made by adding resistors and capacitors to quad op-amps, which are readily available. Some IC versions are made that also provide the necessary good-quality resistors and/or capacitors. These also provide handy formulas, charts or tables, enabling the inexperienced designer to build a working filter with a minimum of thought. An example is the AF100 (National [28]).

Obviously, these switches can be used to build analog multiplexers or demultiplexers. In fact this has already been done by the manufacturers; the switches themselves are similar and the same considerations apply. An additional feature is that rather than having a control line for each switch, a digital code is used to select the desired switch, which minimizes the number of control lines. Since the switches are all tied together on one end, the number of pins is considerably smaller than it would be using individual switches. The switches are bilateral, so a multiplexer becomes a demultiplexer just by redefining the input(s) and output(s). Sometimes it is important whether or not one switch opens before the next one closes, break-before-make, or vice-versa.

A sample-and-hold (S&H) may be thought of as a one-bit analog memory. The usual function is that when the switch is turned on the output follows the input, but when the switch is off, the output remains at the value at the time of turnoff. (Track-and-hold is a more accurate name for this function, but the two terms are used interchangeably.) It consists of an analog switch followed by a memory capacitor and high-input-impedance buffer. Monolithic ICs are available, but the memory capacitor usually must be supplied. Its size is chosen according to the application; a larger capacitance increases the memory time but also lengthens the acquisition time, and vice-versa. Also, a high-quality capacitor must be used or else the capacitor itself will introduce error. The DC leakage of the switch causes the capacitor voltage to "droop". The switch capacitance causes a small step in the voltage at turnoff by coupling part of the control signal into the output.

The HA2420 (Harris[6]) is unique in that it is set up as an op-amp. Normal op-amp configurations are used, and in the track mode error parameters are referred to the input. In the hold mode the noise and input leakage of the output amp come into play.

ANALOG MEMORIES, SHIFT REGISTERS

Memory is one of the outstanding features of digital systems. Many types of memory are available, offering a wide range of capacity, speed and volatility. On the other hand, there is little available to the analog designer. There is tape recording, but that seems to work better when encoded digitally anyway. There is no equivalent of RAM (Random Access Memory).

One type that has recently made great advances and now may be considered useful, is the analog shift register, specifically the CCD (Charge-Coupled-Device). These may be used as serial analog memories. To be useful, charge transfer from stage to stage must be extremely good; for 10% error (equivalent to 1 dB) through a 1000 stage (bit) register, transfer must be 99.99% efficient. This is about the point

There are also dual-tracking regulators, such as the MC1568 (Motorola[5]), where the drift in one supply voltage is supposed to be matched by an equal and opposite drift in the other. Usually, however, supply voltage tolerances are specified independently, and as long as these are met, there should be no need for tracking.

A special class of regulator is the voltage reference. If an ideal regulator existed it would also be an ideal reference, but in practice better voltage accuracy can be obtained by giving up the high-power-handling capability. Similarly, the simplest version is the fixed voltage reference. An example is the AD270X family (Analog Devices[18]) which supply 10.000V, accurate to within a few millivolts untrimmed. It can be used just like a three-terminal regulator, but output drive capability is limited to that of an op-amp. Some references are adjustable over a limited range with minimal effect on performance. The REF-01 (Precision Monolithics[8]) gives 10V adjustable $\pm 3\%$, allowing adjustment to 10.24V for binary-weighted ladders.

There are also two-terminal devices, which appear like zener diodes, although inside is an entire integrated circuit. An example is the LM103-X.X (National[4]), where X.X is any voltage from 1.8V to 5.6V in the standard 5% values.

ANALOG SWITCHES, MULTIPLEXERS, SAMPLE-AND-HOLD

Switching between two or more digital signals is easy, since digital circuits are themselves switches; switching of analog signals is more tricky. The most common type of analog switch employs FETs as solid-state switches. Early versions used JFETs; in fact some consisted of little more than the required JFETs. Newer designs include the circuitry necessary to translate from logic-level control to the rail-to-rail swing necessary to switch the FETs. Probably the best general-purpose types use CMOS, although they have higher channel (series) resistance than JFETs. The switches are typically unbuffered on both ends; furthermore, resistance does vary somewhat with applied signal voltage. Usual practice is simply to keep the load impedance orders of magnitude higher than the switch resistance. DC leakage is small enough to be ignored in most applications. Feedthrough or crosstalk can be a problem at higher frequencies, where leakage capacitance becomes significant. Likewise switching time and switching transients must be considered at the higher switching rates.

The most common type, oddly enough, is actually a digital switch, the CD4016/66 (RCA[23]). It is classified as a digital transmission gate, but is simply a CMOS switch, so it transmits anything. Supply voltage is limited to about 15V (single-ended), but it can handle any signal between the rails. A more general unit is the DG200 (Siliconix[24]), a dual CMOS switch (with drivers) which uses the normal ± 15V analog split supply.

important, although they usually are taken for granted, sometimes with disastrous results.

It is nearly always more cost-effective to buy a line-operated power supply than to design one. There are numerous problems to worry about not found in low-power circuitry: power dissipation, peak currents, overload conditions, fusing, lethal voltage, etc. There are dozens of companies that have been in the business a long time, and usually a suitable power supply can be obtained commercially at a reasonable price. Sometimes it is still necessary to use regulators. For example, either on-board regulators where the system is large enough to require isolation of each board, or a battery-powered system where the expected battery voltage change is intolerable. IC regulators have been around for years. It is best to use a recent design as the newer ones not only have more capability but are nearly "bulletproof", usually at little or no cost penalty.

The oldest is the μA723 (Fairchild[3]), which is a fairly general circuit and is still around. The next step was a "three-terminal" fixed 5V regulator, the LM109 (National[4]). This is an extremely simple device to use, having only input, output and ground. It requires at most two external bypass capacitors, and these may be unnecessary. A more general family is the MC78XX/79XX (Motorola[5]), where the first is for positive voltages and the second for negative, and XX denotes the voltage. Most of this type are protected against thermal (power) and current overloads; they simply shut down temporarily if overstressed. Newer designs offer higher ratings than these, particularly in current. In any case, maximum specified output cannot be obtained unless the corresponding heat sinking specified by the manufacturer is provided. Again, power handling capability is limited by how well heat is conducted away from the chip as with power transistors; indeed, power transistor cases are used for these circuits, and which particular case is used largely determines the power rating.

The number of different power ratings when multiplied by the number of different standard voltages gave a very large number of parts which had to be manufactured and stocked. The designer had a problem with voltages that were nonstandard or required tweaking for maximum accuracy. Ways of "fudging" the specified voltage were devised, but these often had adverse side effects. A four-terminal family, the A78GXX/79GXX (Fairchild[3]) was produced, but these required new packages, and the old layouts, sockets, etc., didn't fit. These were made obsolete by the invention of the three-terminal adjustable regulator, the LM117/137 (National[4]). The ground pin, which was really a reference, became the adjustment pin; voltage was set by a feedback network, not unlike an op-amp. The catch is that the quiescent current could no longer be dumped into ground. It goes instead into the load, defining a minimum load current; this normally presents no problem.

The function generator IC has been described as "a WAVETEK™ on a chip"; indeed with the addition of a few capacitors, pots and switches it performs much as a low-cost laboratory function generator would. It consists basically of an integrator and a hysteresis switch in a negative-feedback loop. This generates square and triangle waves of high quality, at least at moderate frequency. The "sine" wave is not generated as such but is synthesized from the triangle wave by nonlinear shaping networks (e.g., diode limiters to round the peaks). The distortion (harmonic content) is relatively high and can be sensitive to amplitude adjustment and hence to temperature. A symmetry control may be available to change the square wave to a pulse and the triangle wave to a sawtooth. Frequency can be varied or "swept" by a control voltage, usually in linear proportion, over a range as wide as 1000:1. The price is that frequency will vary on its own (modulation and drift), as the control input always has noise and DC drift. This is usually worse at the ends of the frequency sweep and the limits of the frequency range; in fact most parameters degrade somewhat at the extremes. Frequency range is typically from roughly 1 Hz (lower if one is willing to use electrolytic capacitors) to 1 MHz (for 50% duty cycle; less otherwise). The XR-205 (Exar[22]) was about the first; the XR2206 is an improved version. These have all the features mentioned above plus a linear multiplier for amplitude modulation (AM).

For low distortion and good stability at fixed frequency, RC (resistor-capacitor) or IC (inductor-capacitor) oscillators are usually used. These oscillators are available as hybrids or modules only, with no specific monolithics known. They can be built using a few op-amps[12].

For very stable frequency, crystal-controlled oscillators are normally used. These also are available only as hybrids or modules. There is an additional problem that a crystal must be cut to the exact frequency desired, so excepting a few standard frequencies these are custom units and hence have relatively high prices and long lead times. It is usually easier to just order the crystal and build the circuit[12]. Output is usually a square wave. Crystal frequencies range from 10 KHz (below this the frequency must come from a divider chain) to many MHz, beyond the range of ICs.

VOLTAGE REGULATORS, REFERENCES

Nearly all electronic systems have a regulator in them somewhere. If the system is line-powered, the supply is regulated; if it is battery-operated a regulator may be included to stabilize the voltage as the battery discharges. In line-operated systems the most frequent cause of failure is the power supply, and within that the failure is most often in the regulator. In battery-powered systems the battery is the most likely culprit, but the regulator is second. Hence power supplies in general and regulators in particular are very

in phase if desired. This can be possible even if the input signal is contaminated with or even obscured by noise. The input signal need not necessarily have the same waveshape as the output (reference) signal. Thus the PLL has a large number of applications; detecting, tracking or reproducing a signal buried in noise, producing a square or sine wave output from a pulse train, demodulation of FM, phase shifting, and synchronization, to name but a few.

The first, and most common ICs, are the NE560 series (Signetics[9]). The CD4046 (RCA[7]) is a good general-purpose device. It is made with CMOS technology which gives high input impedance, low power consumption and wide supply voltage range; its chief drawback is that it is slow, at least relatively (1 MHz!!!). It requires few external components, offers both common types of phase detectors used in PLLs, and is inexpensive.

There are many other designs, differing widely because there are many variables involved in designing a PLL, depending on the application. One should select a device designed for the same application, or at least one close to it. It is possible that no IC will be suitable. The first consideration is the range of frequencies that the PLL must cover - high or low, wide or narrow. Some types of PLL can track a noisy signal while others cannot; some will track any input waveform while others require 50% duty cycle. It may or may not be of importance what the PLL does when the input signal becomes small, vanishes, or inverts - does the loop remain stable, drift off, head for zero frequency, suffer wild gyrations? How important is the VCO? The application may or may not tolerate noise (unwanted modulation) or a nonlinear control characteristic.

Most designs provide for loops of either first or second order. Second-order is almost always advantageous, with little increase in complexity. Third and higher orders are possible with additional components, but are rarely necessary. There is a classic text[20] on PLLs which is well worth reviewing before designing one. The reader should also be aware of the Frequency-Lock Loop[21] (FLL), a similar but little known device which tracks frequency only; it has advantages and disadvantages relative to a PLL. There are no IC FLLs, but one can be assembled using as few as three ordinary ICs.

OSCILLATORS, FUNCTION GENERATORS

An oscillator is typically a circuit which generates a sine, square, pulse or triangular wave; a function generator typically provides any of these. It would seem then that oscillators are not necessary, especially given that the frequency is voltage-variable for function generators but not for oscillators; but such is not the case. An oscillator usually excels in a certain respect, and cannot be matched by a function generator for certain applications.

designer, and they can have a number of problems. A complete, general-purpose device was the LM170 (National[4]), but it has been discontinued. A simple, well-behaved circuit[12] can be built using an FET as the gain-control element and an op-amp for buffering and amplification; op-amps may also be used for integration and precision rectification if better performance is required.

LOG, ANTILOG CONVERTERS

Logarithms are often used in electronic engineering. The above section pointed out the desirability of using an antilog characteristic in gain control; in fact logarithms often help in handling wide dynamic ranges. Decibels are logarithmic. Converting back and forth to logarithms enables one to easily multiply, divide, exponentiate, root, etc. Many things in nature occur logarithmically, or exponentially, which is simply the reverse. A chain reaction is an example of a geometrical progression, which has an exponential rise.

As pointed out, a silicon semiconductor junction exhibits a nearly logarithmic voltage-current relationship. There are a number of problems in utilizing it, chiefly the strong temperature dependence of the characteristic. These problems are taken care of in integrated devices such as the 8048/8049 pair (Intersil[10]). These are fairly easy to use and work well if the data sheets are observed. Note, however, that they are not linear devices and the effect of errors must be carefully thought out. For example, DC offset at one point may be equivalent to a gain error in the overall circuit, since addition in logs is equivalent to multiplication. Grounding the input will not necessarily produce a meaningful output, as the log of zero is minus infinity. Error is referred to the input of the antilog circuit, as usual, but to the output for the log circuit. Two op-amps are used in both circuits and input offset adjustment terminals provided, but for some applications one or both adjustments are unnecessary. Dynamic range is 60-120 dB on the log end; again the wide range being an attribute of logs.

Note that on the inside the two devices are very similar; they consist of the same parts rearranged. This is true for many other complementary device pairs. Often one device of a pair will do the job of the other when placed in the negative-feedback loop of an op-amp. Hence accuracy, speed, etc., are usually comparable for a a device pair.

PHASE-LOCK LOOPS

A Phase-Lock Loop (PLL) is a popular device which locks a reference oscillator (usually referred to as a Voltage-Controlled Oscillator or VCO) to a periodic input signal in frequency, and also

resistor in series right at the input. (This problem can also occur with the linear multipliers, but it is less likely because they are slower.)

The output(s) are taken across resistors to the positive supply; this causes some problems. Any hum, drift or noise on the positive supply is transmitted directly to the next stage, as the output of the 1596 is a current source. Likewise, any signal impressed on the power supply line by later high-output stages is fed back, inviting oscillation. Fortunately, in most applications the supply is regulated well enough that these problems are not significant. An op-amp differential amplifier can be used on the output to reject common-mode noise, but op-amps are too slow for many applications. If used, the op-amp can also provide buffering and level-shifting. (The 1596 circuitry is stacked totem-pole fashion, so three different levels of DC bias are required.)

GAIN CONTROL ELEMENTS

A specific problem that arises often in analog signal processing is varying the amplitude of an AC signal according to a DC control voltage. This can be done with a linear multiplier, but the expected 1% accuracy limits the reliable dynamic range to about 40 dB because at the low end a small DC error causes a large relative change in AC signal amplitude. Worse yet, an error causing a shift through zero causes the signal to simply reappear with opposite polarity, which may be disastrous, as in feedback systems. It is usually preferable to have an antilogarithmic control characteristic; i.e., a given change in control voltage in volts produces a given change in signal level in dB.

In theory, this can be done by adding the AC signal and the DC control voltage together before passing through an element having an antilog characteristic such as a diode, then removing the DC from the output by AC coupling. The signal amplitude must be kept small compared to the DC control voltage, which is already small, to avoid distortion. This limits the dynamic range, negating the original purpose. A better arrangement is used in the MC3340 (Motorola) "electronic attenuator". Although the same principle is used, the arrangement improves several problems considerably, giving a range of attenuation up to 90 dB with a control characteristic that is more or less antilog.

A similar problem is Automatic Gain Control (AGC), a circuit which maintains a constant output AC signal level over a wide range of input level. There are many ICs available claiming to be adaptable to AGC, as virtually any device exhibiting gain control can be adapted to AGC; the exact control characteristic is relatively unimportant because the device is inside a negative-feedback loop. However, most are rather crude, leaving a lot of work for the

Most new devices, for example the AD532 (Analog Devices[18]), are laser-trimmed internally so the pots are unnecessary. This particular device includes an output amplifier, so nothing need be added. The pre-trimmed types are usually well worth the additional cost. These and most other units perform the computation:

$$V_{OUT} = (V_{X_+} - V_{X_-})(V_{Y_+} - V_{Y_-})/10$$

The quantities in brackets simply indicate differential inputs. The 1/10 is a scale factor so that when both inputs are 10V (full scale), the output is also 10V.

Multipliers can also be used with an op-amp and negative feedback to perform division and extract square roots. These will not be specifically discussed here other than to point out that only one input of a divider is allowed to go negative (two-quadrant division); inverting the other input inverts the feedback and makes the circuit unstable. Likewise, a square-rooter cannot handle negative numbers. Also, the range for the divider has to be set arbitrarily, as one can never divide by zero.

The so-called "multi-function" module, such as the 4301 (Burr-Brown[19]), extends the computation to:

$$V_{OUT} = V_Y (V_Z/V_X)^m$$

so it can do the job of any of the others, but these are not yet available in monolithic form and hence are relatively big and expensive.

BALANCED MODULATOR/DEMODULATORS

A common task in analog circuitry, especially signal processing or control, is multiplication where one input may be clipped. An example is modulation, or frequency spectrum shifting. Here a linear multiplier can be used, but often if only one input is linear and the other clipped, the only difference in the output is the generation of spurious bands at odd harmonics of the carrier (clipped) frequency, at spectrum locations where they may easily be eliminated with a simple low-pass filter. In this application there is a simpler and faster device available, the balanced modulator, or more properly, the doubly-balanced modulator-demodulator.

The most common is the MC1596 (Motorola[5]). It is used like a simplified multiplier, requiring usually only one balance pot and often none. It is fast, having a bandwidth of 80 MHz at the signal input and 300 MHz at the carrier input. In fast circuits such as these, parasitic oscillations at very high frequencies can occur for certain input conditions, primarily long leads on the signal input. The data sheets give circuits to prevent this; the simplest is a 1K

COMPARATORS

A comparator may be thought of as a limited-purpose op-amp. Indeed, an op-amp without negative feedback becomes a comparator. Here the output indicates only the polarity of the (differential) input. It can also be considered a clipper or a one-bit A-D converter. The input section looks like that of an op-amp and has the problems of analog, while the output section looks digital and has the problems of digital. The combination of the two technologies on the same chip becomes a third problem in itself. On the other hand, a comparator is not a linear device and needs no compensation, so it can be made to be faster. In fact, speed is the principal improvement over just using an op-amp. Comparators are fast by analog standards, but slow by digital. The quest for an ideal comparator has been no more fruitful than that for the ideal op-amp.

The original IC comparator, the μA710 (Fairchild[3]), has problems and is obsolete, but is still around. It is relatively fast. The standard, sort of the 741 of comparators, is the LM111 (National[4]); it is slow but well-behaved. The LM139 (National[4]) is a quad having specifications similar to the 111, but some features are lacking as there are not enough pins on the package. There are many high-speed comparators available, but many will not take $\pm$15V or have other drawbacks. There is little interchangeability other than the 111 or 139 types.

MULTIPLIERS, DIVIDERS, ROOTERS

In electronic computation or signal processing it is often necessary to generate the product of two numbers or signals. This is a relatively difficult problem in both analog and digital, at least at high speed. In analog, the invention of the "transconductance multiplier" or "Gilbert cell" made multiplication far more practical (easier and faster) than before. This invention uses the logarithmic voltage-current relationship of a semiconductor junction to convert two signals to logs, add, and convert back with antilog, which taken together is equivalent to multiplication. Moreover, all signals are handled differentially so either input may be either positive or negative (four-quadrant multiplication), avoiding the nasty problem that the logarithm of a negative number is undefined.

The MC1595 type (Motorola[5]) was the first IC version; it left a lot for the designer to do. The MC1594 is an improved version having more of the necessary circuitry on the chip itself. (Don't ask me to explain the reverse numbering.) Up to four potentiometer adjustments are required, although some or all may be avoided in some applications. Static accuracy is on the order of +1% after trimming. Bandwidth (3 dB down) is around 1 MHz, but 1% additional error due to phase shift occurs at 30 KHz, so frequency response is a strong function of the required accuracy.

none of the nice features of op-amps. An old, but still useful, device is the MC1552/3 (Motorola[5]) which has a gain of 34 dB or 52 dB respectively, controllable somewhat with external components, at frequencies up to 40 MHz. This gives a gain-bandwidth product in the Gigahertz region, far exceeding that of most op-amps. It is internally biased for AC coupling and ready to go. The MC1545 (Motorola[5]) is a complete gate-controlled, two-channel-input amplifier having a gain of about 20 dB and a bandwidth of 50 MHz. Inputs are differential, and so is the output; the latter feature is not normally available on op-amps. However, power-supply rejection is not specified, as indeed there is none if single-ended output is used. Also, as with many of these devices, supply voltage must be somewhat less than the ±15V normally used for op-amps. There is nothing approaching a standard for circuits of this class, and little interchangeability.

POWER, AUDIO AMPLIFIERS

In high-power applications it would often be nice to have a device which would have the nice properties of an op-amp but could handle the high power. Significant advances have been made in several directions, ranging from high-voltage (PA08, Apex [15], ±150V) or high-current (L465, SGS-ATES [16], 4A) op-amps in small packages to power supplies which are configured like an op-amp (Kepco [17]) and supply up to ±20A or ±72V (basically DC).

The specific problem with linear devices is to remove the heat generated from the chip, which must be done by heat flow out through the case and into something else. Not surprisingly, the most common package is a modified TO-3 power transistor package with extra leads. Unfortunately the pinout (and even the number of pins) is not standard, so there is not a lot of interchangeability. This author's favorite is the µA791 (Fairchild[3]). The front end is just like a 741; however, external compensation is required. The output is capable of 15W, ±22V and ±1.25A (not necessarily simultaneously or continuously). Due to the convenient placement of the (external) current-limiting resistor, multiple units can be paralleled directly, which is not normally true of op-amps.

There are also a number of current-boosters, devices having only unity voltage gain but high current gain, such as the MC1538 (Motorola[5]), which can be inserted after an ordinary op-amp but still within the feedback loop to increase its current capability with essentially no change in the other properties.

(c) Motorola [5]
MC1558 - dual 741-type
MC4741 - quad 741

(d) Harris [6]
HA2400 - "programmable" (selectable); four input stages tied to common output stage
HA25XX, 26XX - several wideband types
HA46XX - quad wideband

(e) RCA [7]
CA3060, 3080 - "transconductance" amplifiers, can be used like op-amps with special properties
CA3130, 3160 - MOSFET input, CMOS output, near infinite input impedance, output swings rail to rail

(f) Precision Monolithics [8]
OP27, 37 - low noise

(g) Signetics [9]
NE5539 - ultra high frequency

(h) Intersil [10]
ICL765X - chopper-stabilized; extremely low input offset

(i) Texas Instrument [11]
TL06X, TL07X, TL08X - JFET-input family; singles, duals, quads, low-power, low-noise, general-purpose

Op-amps are covered in detail in a companion report [12], so they will be discussed no further here. For a very thorough book, see Reference 13. Reference 14 is recommended for those knowing little electronics; it is simple, but well done.

Op-amps are fairly well standardized; in fact, a general-purpose op-amp is often referred to as a "741-type", even though it may be completely different inside. Pinout is more or less standard, and in many cases one type may be removed and another type plugged in with no adjustments and no noticeable change in performance. Unfortunately, as we shall see, this is the only type of analog IC where this is true.

WIDEBAND, IF-RF, DIFFERENTIAL, VIDEO AMPLIFIERS

This is a class of amplifiers, going by many names, which fills the need for amplification at frequencies too high for op-amps. They are not intended for feedback, and hence are useful for little other than fixed-gain amplification. Many are quite crude and have few or

(d) The op-amp has a differential input; it is sensitive only to differential input signals. Changing both inputs by the same amount in the same direction (common-mode) has virtually no effect on the output. By definition then, changes in power supply voltage, which can be thought of as unwanted signals, have no significant effect on the output. Likewise, changes in the output load, which can be thought of as injecting an unwanted signal into the output, do not change the output appreciably.

(e) The op-amp's gain is high, much higher than that of the circuit in which it is embedded. Circuit gain is set by external passive components and does not depend directly on the op-amp gain.

(f) Likewise, the op-amp's frequency response should be much higher than that of the overall circuit, and should not affect the circuit's response.

Op-amps are basically medium-speed (medium-frequency) devices. Although the typical unity-gain bandwidth is around a Megahertz, at this frequency the gain condition given above is obviously violated. Typically op-amp circuits are limited to about 10 KHz. This can be considerably lower, especially if low-power op-amps, which tend to be slow, are used. On the other hand, it can in cases be pushed considerably higher, and special op-amps are available which can be used in the Megahertz range. High speed is obtained at the expense of some other parameters, however, and at this frequency devices other than op-amps should be used if possible.

A list of all known op-amps and variations contains about 4000 entries[2]. Below is a partial list of manufacturers, with some examples of interesting milestones (by generic number; "X" means various numbers):

(a) Fairchild[3]
- μA702 - original IC op-amp
- μA709 - oldest IC op-amp still in use
- μA741 - first internally compensated, protected; still the general-purpose standard
- μA748 - 741 without compensation
- μA776 - "programmable" (bias controllable); can be low-powered or turned completely off
- μA791 - power op-amp, 1 amp output

(b) National[4]
- LM10X - several low-input-current designs
- LM118 - first compensated high-speed; still the standard
- LM15X - JFET input family; very high input impedance
- LM1900 - quad "Norton" or current amp; not ordinary op-amps

CHAPTER 5

ANALOG IC FUNCTIONS AVAILABLE

OPERATIONAL AMPLIFIERS

The mainstay of the analog world, accounting for about half of all analog IC sales, is the operational amplifier, abbreviated op-amp or simply OA. The name is a holdover from analog computers, where they were indeed amplifiers used for performing operations such as summation, subtraction, inversion, integration, differentiation and, of course, amplification. They survived because of their extreme generality; they have proved useful as buffers, filters, oscillators, controlled voltage and current sources, impedance converters, precision rectifiers, peak detectors and log converters, to give but a partial list.

What is an op-amp, to be so useful? It is the closest thing we have to that impossible dream, an ideal amplifier. It is usually thought of as a high-gain voltage amplifier, although it also has high current gain. Taken together these two attributes imply high power gain. This is really the fundamental quantity, although it is rarely even mentioned. The output of the amplifier does something, virtually independent of the load put on it, in response to a command from the input, which places virtually no load on what it is sensing. The specific attributes may be summarized as follows:

(a) The op-amp is normally a low-power device, roughly ±15V, ±10ma, 500mw, although some specialized devices are available to much higher ratings. The purpose of the op-amp is to handle signals, not power. It can, however, in many applications be used to control power-handling devices quite nicely.

(b) Op-amps are normally used in linear or quasi-linear circuits. They require negative feedback to set the gain, operating function and DC bias and to ensure linearity. This means they usually need compensation to be stable (i.e., not oscillate). Nowadays the manufacturer usually includes this internally; if not, compensation methods are given.

(c) The op-amp's response includes DC, and its DC performance specified.

A relatively new type of filter is the switched-capacitor filter. This uses the concept that a capacitor repeatedly charged and then discharged into a load at a relatively high frequency provides some average current which is proportional to both applied voltage and frequency, and hence, on the average, looks like a resistor whose value is set by a (digital) clock frequency. This is attractive for ICs because it eliminates resistors and instead makes the filter (cutoff) frequency dependent on a ratio of capacitors, which can be more closely controlled in contemporary IC technology. Furthermore, the filter frequency can be set by an external clock frequency, so it may be both extremely accurate and easily variable. There are naturally some disadvantages. The filter cannot pass DC. There is clock frequency feedthrough in the output; this can be rather large, but can often be removed by a simple RC low-pass. The frequency range is somewhat restricted, as the clock frequency must be about 100 times higher than the filter frequency. An example is the MF10 (National[4]); here summing resistors are added externally, so any filter function may be realized. There are others which are dedicated to a specific function, so only the frequency may be varied.

Another type that has recently become available to a limited extent is the transversal filter. This consists of an analog shift register (CCD) with the "taps" summed with varying weights and sign. Thus, it is unusual in that it is realized in the time domain rather than the frequency domain. This gives it some unique properties, chiefly finite impulse (time) response and inherently-linear phase capability. Again, there is noise at the clock (shift) frequency. Most of these are designed for specific applications and are not generally available.

ANALOG-DIGITAL-ANALOG CONVERTERS

A-D and D-A converters are very important in many "digital" systems, as it was pointed out that the real world is mostly analog. They are in fact often the limiting factor on the performance of these otherwise-digital systems. These devices are really small subsystems in themselves. Their design is relatively difficult, as they must meet the standards of both the analog and digital worlds, which tend to be mutually exclusive in many respects. A great deal of time and money has been spent on the problem; some companies subsist principally on their sales.

Monolithic designs for years lagged in performance, but great strides have been made in the last few years. Accuracy has been improved greatly by laser and other trimming methods. Speed is now being pushed higher. The competition has brought a good deal of "specmanship"; the user should read all the fine print to determine whether the low-order bits are meaningful. For instance, note that resolution does not mean accuracy. Past 10-bit accuracy (0.1%) one must be very careful with the analog circuit techniques or the available accuracy will be lost.

There are a number of other things to be considered when selecting an A-D or D-A. Several different digital codes are used, particularly when negative numbers are involved; even for a given code the bits may be numbered differently by different companies. Some units will operate from single-supply and still include ground (0V) in the input range; others require odd supply voltages. Some are less than complete, requiring perhaps external reference voltage, comparator, clock, or output buffer. On the other hand, some DACs (i.e., CMOS) will accept a reference voltage of either polarity, so they can actually multiply an analog signal by a digital number (fraction); these are called Multiplying DACs (MDACs). Recent designs often include a number of auxiliary features, such as sample-and-hold or digital memory buffer.

There is not much in the way of standards or interchangeability. The variety is so great that none will be mentioned here. Most A-Ds contain D-As, but single devices usable as either are not made; the technology has simply become too specialized.

VOLTAGE-FREQUENCY-VOLTAGE CONVERTERS

A kind of specialized A-D conversion circuit is the Voltage-to-Frequency converter (V-F), with its counterpart, the F-V. The V-F converts an analog voltage (or possibly current) to a square wave or pulse train, usually having a frequency in direct proportion. As with the VCO, accuracy is less at the ends of the ranges; in particular, zero frequency is undefined, so the lower end of the range is measured at some arbitrary point slightly above zero.

V-Fs are useful as a wideband FM generator to transmit information over a channel of quality inadequate for direct transmission, e.g., to transmit a DC reading over telephone lines. When used as a transmitter, the maximum input frequency is limited by the Nyquist sampling theorem (half the sampling frequency, absolute max). This means that the bandwidth goes down at the lower end of the scale (lower frequency), and in fact would go to zero at zero frequency. When used as a receiver (F-V), the pulses must be smoothed in a low-pass filter, so again frequency response is obviously limited.

A V-F may also be used to make a long-time-constant integrator. (Conventional op-amp integrators are limited to time constants of a few seconds.) If the analog signal is first converted to frequency, integration may be done by a digital counter chain and the integration time increased almost without limit by adding more counter stages. Note, however, that the low-order bits are not necessarily accurate; accuracy is still limited by the accuracy of the V-F, i.e., about 10 bits for a 0.1% converter.

An example is the LM131 (National[4]). It functions as either a V-F or a F-V, will operate from single supply and work at zero input, and goes up to 100 KHz. There are other types that go to 1 MHz and beyond.

TIMERS

The NE555 timer (Signetics[9]) has been called the most popular analog integrated circuit ever produced. If this is true, it is not clear why it is so. It is simply a multivibrator, either monostable or astable. However, things that flip and flop always seem to fascinate engineers. The job can be done by op-amps or comparators with the addition of a few extra parts, which the 555 mostly requires anyway. Accuracy of the device itself is good, but note that the timing capacitor and resistors must be of high quality to maintain the accuracy. Some aspects of the device can be confusing, such as a negative-going level being required to trigger an input.

Dual and quad versions are available, but do not have all the options because there are not enough pins. There are newer versions, particularly in CMOS, which claim to have better behaviour.

NOISE; PSEUDONOISE GENERATORS

In a sense, the opposite problem of generating a signal is generating noise. Noise is generally thought of as an unwanted signal, but there are times it is wanted, for example in testing systems to see how they perform in the presence of noise. The most common type of noise is random, white, Gaussian noise. Random simply means that it cannot be predicted exactly; only statistically. White means flat (constant) frequency spectrum, at least across some band of interest. Gaussian refers to the amplitude probability distribution and is characteristic of many processes, primarily those which are really a sum of a large number of similar but independent events. It might seem that it would be difficult to generate a signal that is random in time but predictable in statistics; this is partly true. True-noise generators are usually made by simply taking the signal from a noisy component and amplifying it up to a usable level. However, devices that are especially noisy usually are so because of defects, and a device with defects is likely to get worse with time. There are some ICs available which provide true noise, but none are very widely known.

A more common, very clever device is the pseudonoise generator, also called pseudorandom binary sequence generator, or other variations. It consists of a digital shift register with feedback. The input is taken as the exclusive-OR (EOR) of the output and one or more intermediate stages. For certain combinations of "taps" the register will cycle through all possible states less one in a random-appearing fashion before starting over. Some precaution must be taken to insure that the shift register does not somehow get into the other state (i.e., all zeros), because it is stable and the

register will just sit there. Since assembling a large number of digital stages is no problem, the cycle time can easily be made days or even years, so the output appears random even though the waveform is actually precisely determined.

The frequency spectrum is of the form (sin f)/f with the first zero at the clock frequency. This is quite flat near zero, and typically the clock frequency can be made high enough that the spectrum is white over the range of interest. Since the signal is really periodic, the spectrum is not truly continuous, but consists of lines, spaced at the repetition frequency. Similarly, this frequency may typically be made in the microHertz range, so this is not noticeable. The amplitude of the raw signal is either 0 or +V, clearly not a Gaussian distribution. But again, if only the lower part of the spectrum is selected by a linear low-pass filter, the signal at any moment is the average of a large number of essentially independent events (bits), the (Central Limit Theorem) condition for a Gaussian distribution. Since one can be built with a shift register, clock oscillator, EOR gate and maybe a simple low-pass filter, there isn't much need for an IC. However, some are available, such as the MM5837 (National[29]).

CHAPTER 6

GENERAL PRECAUTIONS

Most disciplines entail certain things the novice finds out the hard way; this is surely true of analog. On the other hand, the experienced designer often will see a circuit work at least approximately correctly on the first try. This section will attempt to list some of the more common pitfalls, based on experience, so the reader might avoid some problems.

The newer circuits are pretty much damage-resistant, but no circuit is completely immune. It is always wise to connect the circuit correctly. With analog circuits a split supply (equal positive and negative voltages) is usually used. (Note that this means two supplies, each with one side connected to ground; not just a single supply tied between plus and minus, which leaves ground undefined.) If so, both should be turned on and off together, as having only one supply on may result in biasing conditions the circuit was never intended to have; using a dual supply makes this precaution automatic. Most circuits will withstand any voltage up to either supply voltage being applied to any input or output, but check the spec sheet before doing so. Extra terminals such as compensation or offset terminals are usually not so protected. Do not connect anything to "unused" pins, as these may actually be used internally. Few circuits will survive having a power supply applied backwards.

Having the power supply turned off is equivalent to 0V supplies; the circuit is then not guaranteed to withstand any voltage at all, not even a signal applied to the input. Modern types usually survive, but in some cases damage can be done by a low-impedance source such as a 50-ohm signal generator or a charged capacitor. In particular, integrators and filters employ capacitors which, when power is turned off, must dump their charge somewhere, often into the nearest IC. This seldom causes damage, but if a circuit works the first time and never again, some protection diodes could be required.

Except when switching, most digital circuits are in a saturated state and there is no gain to be had, so there is no possibility of unwanted oscillation. Analog ICs, on the other hand, usually possess high gain and are biased in the linear region, and precautions should be taken. A good ground is a necessity; at least a heavy,

low-impedance ground bus is required and a ground plane is highly recommended. Power supplies should be well-regulated with heavy leads and bypassed to ground with good capacitors every few inches on the circuit board. Output leads should not be laid directly alongside input leads; put a ground lead in between as a shield if necessary. Observe that an oscillating circuit cares not at all what the input frequency is; do not use special high-frequency devices where a general-purpose one will do. On the other hand, be not upset if your circuit begins to oscillate when the input is disconnected; a perfectly legitimate circuit may be unstable with the driving impedance removed, as it is part of the circuit.

Circuits should be on PC (Printed Circuit) boards, with one side dedicated completely to ground plane and power supply leads (which are also ground as far as AC signals are concerned). General-purpose wire-wrap boards are undesirable; analog circuitry will not tolerate long leads laid together, which tends to preclude automatic layout. For temporary breadboarding, the "push-in" breadboarding strips having a 0.1 inch grid work surprisingly well, especially if care is taken in layout, bypass capacitors are used liberally, and leads are kept as short as possible.

High impedance circuits present special problems, and the trend in analog is indeed toward higher impedance, in order to minimize power dissipation and also capacitor size. Keep PC leads apart as much as possible, as they have higher capacitance and lower insulation resistance when spaced closer. Furthermore, it has been determined that over a period of time closely-spaced leads tend to form conducting paths between them, which may be deep within the circuit board and not visible. Troubleshooting is difficult; the usual 10 Meg oscilloscope probe will affect the behaviour of megohm circuits appreciably, and other types of instruments often have lower impedance yet. A simple buffer may be constructed by connecting an FET-input op-amp as a voltage follower; this gives typically an input impedance of 10^{12} ohms and a few picofarads, at the expense of a few millivolts of DC offset and perhaps a slight loss in speed. The circuit board must be clean and free of flux, manufacturers' claims notwithstanding. If used in uncontrolled environments the circuit boards should have a conformal coating for protection.

CHAPTER 7

DEBUGGING

When a circuit is assembled, especially for the first of a kind, there is a good chance it will not work, or at least not meet the desired specifications. The first reaction is typically panic, followed by disgust. One hopes that an IC is bad, but suspects rather that the design is faulty. Usually neither is the case. Because of the wide variety of analog circuits it is difficult to define a general procedure that will locate any fault. However, there are a few common problems and hence some guidelines; most can be traced to common sense.

First, check the easy and the obvious: Double-check the layout, connections, and part types. Look for loose connections, damage, solder splashes. Change the IC only if it is socketed and easily replaceable. Check the power supply voltages on the board. (This author has more than once spent time checking a circuit where the power supply was turned on but not connected; high-impedance circuits such as CMOS will sometimes work partially without a power supply!)

Next check all nodes for correct signal and DC bias voltage, beginning at the input of the circuit and working toward the output. Use an oscilloscope; a meter defines one variable only and may well not show the problem. (A frequency counter gives only the number of zero-crossings and tells nothing about the spacing or waveshape; a DC meter gives only the average value and says nothing about fast fluctuations.) It may be necessary to separate the circuit into smaller parts to eliminate interactions or to isolate the problem.

Feedback systems are especially difficult to troubleshoot because of interactions. They may constrain some variable to be correct in spite of a problem. (This occurred in both cases cited above.) An incorrect value may be caused by something far downstream. One must check all the way around the loop to find the beginning of the problem. Sometimes it is necessary to break the feedback loop; expected performance is usually quite different then, but the circuit may be checked serially for the proper (revised) performance.

When developing a new circuit be advised to build two units, even if only one is needed. This may sound wasteful, but it often pays for itself in time saved. Comparing two units should quickly pinpoint a bad part or a single wiring mistake; conversely if two units exhibit the same misoperation, a more basic problem is indicated. Also, any changes should be made to one board at a time, and "before" and "after" performance compared directly to make sure that the progress was not negative. And even if the circuit works the first time, it is nice to know that it is not so touchy that it cannot be duplicated if necessary.

CHAPTER 8

CONCLUSION

Seven years ago it was claimed that, far from dying, analog was growing rapidly and getting better. That certainly proved true, and the indications are the same today. Analog has become easier for the designer in the respect that newer devices are closer to the ideal models; circuits from seven years ago can easily be improved with today's offerings. On the other hand, it is more difficult in the respect that there is much more available and hence much more to know, at least to make state-of-the-art designs.

Also, seven years ago all parts were virtually new; there was no such thing as a discontinued-parts list. Today the industry is going through a mild "shakeout". Announcements of discontinued parts occur almost daily, sometimes immediately after the initial announcement of production. However, the technology has become widespread enough that announcements of second sources are frequent, sometimes coming with the original product announcement. For example, an announcement of a second-source agreement for the 791 power op-amp was replaced a few months later by one for complete discontinuation instead. However, soon after that, plug-in replacements were announced by four other companies.

Where is analog going from here? The best guess is probably in the same direction at the same speed; that is, we can expect constant, evolutionary progress with a few revolutionary breakthroughs thrown in. The world is clearly going digital in the sense that a higher percentage of things are being done with computers, or at least with digital techniques. But there is still plenty of room for analog; in fact, analog clearly has a big job to do. This bare summary has become a fairly long report. To paraphrase a popular saying, analog may be only number two, but it's way ahead of whatever is in third place.

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